USE OF INTEGRATED VEHICLE HEALTH MANAGEMENT IN THE FIELD OF COMMERCIAL AVIATION

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Abstract

In the early days of analog aircraft systems, the notion of Built-In Test (BIT) was nothing more than a simple pushbutton that supplied current to the internal circuitry. If sufficient circuit continuity was detected, a green light would illuminate signifying a successful test. Known as push-to-test or go/no-go systems, this simple approach sufficed for early analog systems. With the advent of digital avionics computers in the early 1980s, however, the ability to detect faults and isolate them to the offending component posed a significant challenge to airline mechanics and repair technicians. Working with industry, Aeronautical Radio, Inc. (ARINC) developed the first aviation industry standard that specifically addressed health management, ARINC-604 "Guidance for Design and use of Built-In Test Equipment." From that standard, the field of Vehicle Health Management (VHM) in commercial aviation was born, although the acronym VHM would not come into common usage in aviation until nearly 20 years later[2]. In the years that followed ARINC-604, additional industry standards have been developed, driven by the advances made as new aircraft families were introduced. Even today commercial aviation has begun to adopt techniques used in other industries, for example, process control and automotive.

Often times, it seems that the definition of Integrated Vehicle Health Management (IVHM) is as varied as the individuals providing the definition. For the purposes of this paper, a common definition is presented that answers the questions "Why IVHM?"; "Where is IVHM used?"; and "What are the safety & economic benefits of IVHM?" Once established, the common definition is used as the basis of discussion for several state-of-the-art, IVHM commercial aviation systems. For each system, a high-level overview is provided, emphasizing the key features of the system and significant differences from previous systems. For those systems already fielded, the challenges, lessons-learned and benefits that were achieved are discussed. For those systems currently in development, the anticipated challenges and benefits of the new systems are discussed. Finally, a glimpse into the future direction of IVHM for commercial aviation is provided, suggesting those areas in which further improvements are necessary.

Introduction

Vehicle health management should be familiar to anyone who has ever operated or ridden in a vehicle, regardless of the type. VHM encompasses the set of *activities that are performed in order to identify, mitigate and resolve faults with the vehicle* (Aaseng, 2001). These activities can be grouped into four phases, as illustrated in Figure 1.

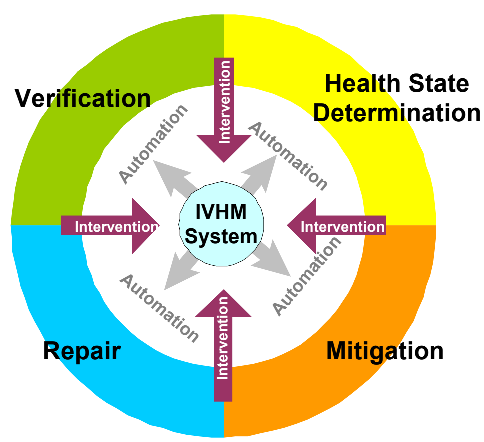

Figure 1 Health Management Activity Model (Aaseng, 2001)

Health State Determination - using diagnostic and prognostic algorithms to monitor, detect and isolate system faults.

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[1] NASA ISHEM Forum 2005, paper #12; September 8, 2005

[2] The space community was one of the early adopters of the VHM acronym, appearing in the literature of the late 1980s.

Mitigation - assessing the impact of the failures and modifying the mission to compensate.

Repair - performing activities to replace or repair the failed components.

Verification - performing activities to ensure that the repairs were performed correctly and that the system has been returned to full operational status.

While many of the phases can be performed manually, IVHM provides an opportunity to augment the activities using automated systems.

Defining IVHM

To fully realize the benefits of IVHM requires the development of a common definition, one that can be understood by all stakeholders. *IVHM should not be treated as a stand-alone subsystem, added on to the vehicle. Nor should a group of sensors and related instrumentation system be considered IVHM. From a software perspective, IVHM is more that just fault models, algorithms and sensor processing software. While IVHM utilizes these components to perform its intended function, a true IVHM system incorporates a philosophy, methodology and process that focuses on design and development for safety, operability, maintainability, reliability and testability. To be most effective, IVHM must be "designed in" to the target system…from the beginning of the program, and not "added on" along the way* (Scandura, 2005).

Health Management Integration

In order to fully realize the benefits of IVHM, coordination and integration with the rest of the program must occur. The notion of *health management integration* ensures that IVHM is properly designed into the system, and involves the establishment of policies and processes that are enforced across the design of the vehicle and supporting systems. As described in (Scandura, 2005), examples of Health Management policies and processes include:

- Fault detection and isolation philosophy;
- Optimal sensor quantity & placement guidelines;
- Standard BIT designs and practices;
- Metrics (e.g., Fault coverage %, fault isolation accuracy %);
- Verification & validation plans and procedures;
- Fault modeling guidelines; and
- Interface standards between subsystems and Health Management.

The role of the Health Management Integrator involves working with the vehicle manufacturer to define these policies and processes. Once these are established, the Health Management Integrator provides both program and technical oversight of the subsystem vendors to ensure the policies and processes are consistently applied across all subsystems.

The ultimate goals of Health Management integration are to ensure an optimal IVHM balance across the system; improved testability, isolation of failures; improved system safety and reliability; and reduced life-cycle costs.

Layered Approach to IVHM

IVHM should be viewed as a series of layers, in which each layer performs a portion of the overall IVHM function (see Figure 2).

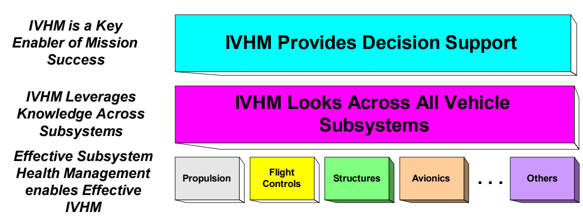

Figure 2 Layered Approach to IVHM (Scandura, 2005)

It is crucial to build IVHM upon a strong foundation of Subsystem Health Management (SHM), provided by the embedded BIT capabilities within the subsystem. The primary purpose of SHM is to ensure *safe operation*, i.e., each subsystem is required to ensure a specific level of safety at the subsystem level, and to mitigate those hazards contributed by that subsystem to the operation of overall vehicle. Hazards in this context include both those posing a danger to vehicle occupants, as well as those affecting the general public and/or environment in which the vehicle operates[3].

The secondary purpose of SHM is economic, i.e., its contribution helps to reduce life cycle cost through improved maintainability, testability and reliability. Commercial aerospace experience has shown that nearly 95% of aircraft life cycle costs are attributable to maintenance activities. In summary, without adequate SHM, the effectiveness of the overall IVHM system will be severely limited.

Looking across all subsystems allows IVHM to assess the overall vehicle health. As described in subsequent sections, many of today's aircraft employ some type of central maintenance system that fulfills the role of collecting faults from all subsystems, performing root-cause determination and recommending repair actions.

Finally, by integrating vehicle health and vehicle operations one can maximize the benefits to the overall system. As depicted in Figure 3, IVHM provides decision support capabilities to all facets of the mission.

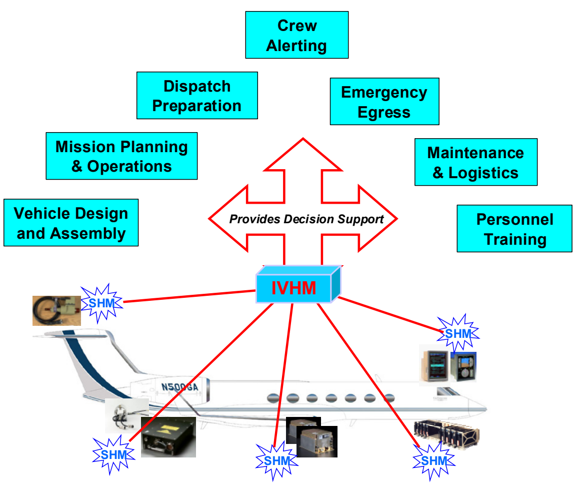

Figure 3 IVHM Provides Decision Support (Scandura, 2005)

The intended use of IVHM data depends upon the business case for the particular market segment and application. One must determine if the available IVHM data creates the necessary value for the users (e.g., maintenance crew, flight crew, airline operator, vehicle manufacturer, etc.).

In addition to business needs, the IVHM system design (physical architecture and the design processes) must support the safety and criticality needs of the consumers of IVHM data. Traditional maintenance systems have been used at the end of the flight to repair the aircraft, rather than during the flight to operate the aircraft, and have therefore been classified as non-critical systems. On the other hand, the Crew Alerting System (CAS) is used to determine the overall functional capability of the aircraft and plays a significant role in the operation of the aircraft; therefore the FAA typically classifies CAS has as a critical system (Scandura, et al., 2004). Satisfying such a broad spectrum of users emphasizes the need to determine the entire user community for IVHM data and ensure the proper level of design assurance is applied to address their needs.

Evolution of Commercial Aviation IVHM

First Generation Systems

Early commercial aircraft were composed primarily of mechanical and analog systems. Testing the functionality of a device typically employed nothing more than a simple pushbutton that supplied current to the internal circuitry of the device. If sufficient circuit continuity was detected, a green light would illuminate signifying a successful test. Referred to as push-to-test or go/no-go test, these could loosely be considered as the beginning of BIT.

Second Generation Systems

Starting in the early 1980s, commercial aircraft began to employ digital systems using electronic hardware and software to perform functions previously performed by mechanical and analog systems. These new digital systems posed special challenges to aircraft mechanics, as the ability to troubleshoot a "black-box" was limited to the indications provided by the system. Industry and ARINC worked together to develop the first standard for health management, ARINC-604 "Guidance for Design and use of Built-In Test Equipment." As the industry began following this standard, digital systems, typically consisting of one or more Line

[3] This latter class of hazards is of particular importance when evaluating SHM/IVHM requirements for unmanned vehicles and robotic systems.

Replaceable Units (LRUs), used dedicated front panels with push-buttons and simple display capability (e.g., lights, alpha-numeric readouts) to provide the mechanic with the ability to test and query the system.

By the mid 1980s, the advent of centralized display panels shared by several LRUs came into use, providing the mechanic with one place to test and query several systems and theoretically reduced the training required to learn the individual systems. First introduced by Boeing and Rockwell-Collins on the 757/767 aircraft, the Maintenance Control and Display Panel (MCDP) provided the mechanic the ability to determine the health of various aircraft subsystems (Aviation Today, 2004). The MCDP displayed alpha-numeric codes that indicated the suspect LRU and fault type. These codes were then cross-referenced in a maintenance manual to determine their meaning and applicable resolution procedures.

Soon thereafter, Airbus introduced the Centralized Fault Display System (CFDS) on the A320 aircraft in 1988. Conceptually similar to the MCDP, the primary innovation of CFDS was the display of English text to the mechanic, eliminating the need to look up cryptic codes in a manual. This accelerated the repair process, pointing the mechanic to the potential problem source quicker, although accessing the necessary resolution procedures still required a trip to the paper manual (Aviation Today, 2004).

Third Generation Systems

While the advances provided by centralized display panels were a welcome addition to the mechanics toolbox, it wasn't until the emergence of centralized maintenance computers in the late 1980s and early 1990s that mechanics would truly benefit. These new centralized systems consumed heath and status data from several LRUs, performed fault consolidation and root-cause analysis, directing the mechanic to the offending system that required repair or replacement, as well as pointing the mechanic to the applicable maintenance procedure. Referred to as the Central Maintenance Computer (CMC) or Onboard Maintenance System (OMS), these new systems were the result of further work by the avionics and aircraft industry to produce updated standards, including ARINC-624 "Design Guidance for Onboard Maintenance System." A prime example of the new CMC technology was introduced by Boeing and Rockwell-Collins on the 747-400 aircraft in 1989. Accessible via a cockpit-mounted display unit, the CMC served a key role in aircraft debug and repair, providing the mechanic with the health of all reporting systems, as well as a method of initiating specific ground-tests to further debug and isolate problems.

Federated vs. Modular Avionics Systems

For many years the traditional approach to aircraft avionics had been federated, that is, one or more physical LRUs dedicated to the performance of each aircraft function, with dedicated connections to control panels, sensors and affectors. The introduction of the Boeing 777 aircraft broke with the federated tradition, choosing instead a modular approach in which multiple functions were hosted on generic Line Replaceable Modules (LRMs), e.g., processing modules, aircraft I/O modules, communication modules and database modules. These modules shared a common infrastructure, mounting them in a rack providing power, cooling and databus connectivity. Doing so benefited the overall aircraft by requiring fewer "black boxes" resulting in a considerable reduction of the amount of weight, power, cooling, volume and wiring required for avionics.

Although the benefits of a modular avionics system were many, it was identified that troubleshooting and repair of such a system would pose a major challenge, if not properly addressed during aircraft design. Mechanics were well-versed in the repair of federated avionics systems. Because most functions are hosted in their own dedicated LRU, failures in a particular system typically result in the removal and replacement of that LRU. "Shotgun troubleshooting" was common, e.g., if a problem occurs in the left LRU, it can be swapped with the right LRU. If the problem follows the LRU, it is most likely the LRU. In a modular system, however, functions no longer enjoy dedicated LRUs. Rather than a Flight Management function being hosted in a dedicated computer, it now lives in a processor module, receiving aircraft data from an I/O module, using navigation data stored on a database module; all three receiving power for a power supply module. Failures of the Flight Management function could be attributed to faults in any of the modules, as well as the mounting rack. It would be difficult, if not impossible, for the mechanic to determine which module is the cause of the problem without additional information from the system. It was clear that such avionics system would require the functionality provided by a CMC, but one more flexible and capable than earlier designs.

Fourth Generation Systems

Continuing to improve on the CMC concept, Boeing and Honeywell introduced the next generation CMC, as part of the integrated avionics suite on the 777 aircraft family in 1995. Unlike previous CMC designs that used hard-coded logic and a rules-based approach to fault consolidation and root-cause analysis, the 777 CMC employed a model-based technique, in which cause-effect relationships and fault propagation paths were captured in a loadable database, using ground-based tools. This approach reduced the engineering effort needed to customize the CMC for a specific aircraft, unlike previous CMC designs that required significant effort to change and adapt.

Additional improvements over previous designs included portable maintenance displays, allowing the mechanic to bring the display closer to the area of repair, rather than running back and forth from the cockpit. The displays were also updated to include more detailed fault information, with basic remove and replace procedures. Finally, since pre-provisioning is often desired by operators so they can be ready with the necessary parts to fix the aircraft when it lands, a limited ability to downlink CMC data to the ground was provided.

The Next Generation

As illustrated in Figure 4, the evolution of VHM in commercial aviation has spanned several generations and aircraft types. That evolution continues today with the state-of-the-art IVHM Systems described in this paper. These include the Primus Epic® CMC, an essential part of the modular avionics system used on several business jets, regional aircraft and rotorcraft; the Crew Information System/Maintenance System currently in development for Boeing's new 787 Dreamliner; and Honeywell's Intelligent Vehicle Sense & Respond program.

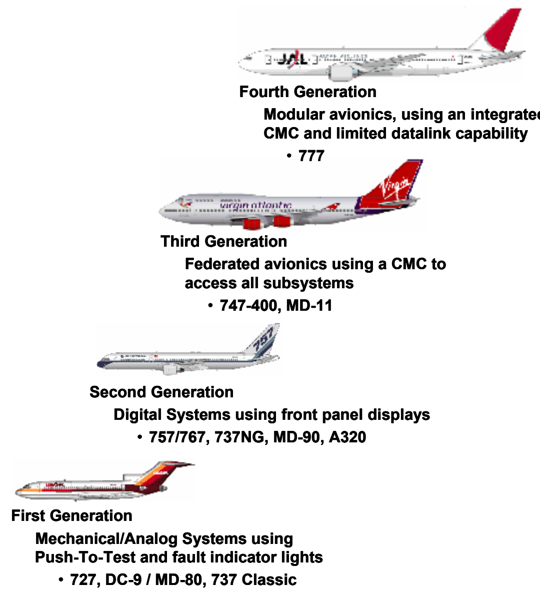

Figure 4 VHM Evolution for Commercial Aircraft

Primus Epic CMC

High-Level Overview

The Primus Epic avionics system represents the next generation in modular avionics systems. Receiving initial FAA certification and entering into service in 2003, Honeywell's Primus Epic system was designed to be scalable and extensible to aircraft and rotorcraft produced by various manufacturers for various markets, rather than targeting a specific aircraft. As of this writing, Primus Epic systems are flying on numerous business aircraft, regional aircraft and rotorcraft.

Integrated within the system, the Primus Epic CMC represents an evolution of several maintenance features used in previous systems. Taking advantage of advances in personal computer (PC) technology, the CMC is hosted on a dedicated LRM that utilizes a commercial-off-the-shelf (COTS) operating system, commonly found in desktop and laptop computers. This approach enables the use COTS hardware, software and communications protocols, which provides the ability to create CMC interface consoles and configuration tools using a PC, instead of specialized hardware.

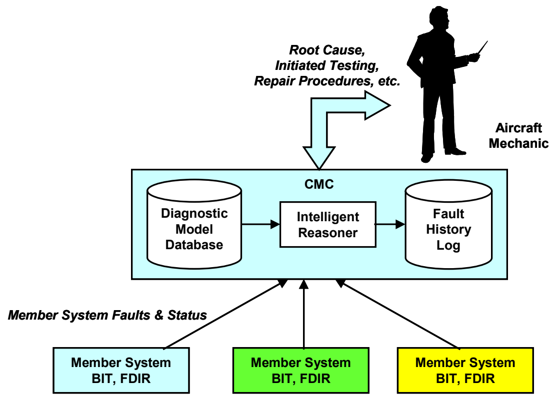

Figure 5 Primus Epic CMC

The PC architecture that the CMC is built upon opened up a great deal of storage capability within the module. As illustrated in Figure 5, this storage capability is used to record all Maintenance Message and CAS message state changes. Most previous systems depended upon a command-response protocol to get this type of data from participating systems during the maintenance session. The CMC is able to access this data directly from its local storage. This feature allows more elegant fault processing algorithms to be built within the CMC to support root cause fault identification. The local storage also speeds up retrieval of fault data. The storage algorithms allow line mechanics to identify "noisy" systems or messages on a given aircraft, or on several aircraft. Previous systems had limited fault storage and stored Maintenance Messages with a counter to indicate how many times the message occurred.

Key Features

Separating Critical & Non-Critical Functions

The Primus Epic architecture is specifically designed for fault tolerance and redundancy. This approach is driven into the Crew Alerting System and the Maintenance System. The separation of these systems is driven by the need for availability and dispatch without a functional CMC. The design objective is to remove the CMC from any dispatch decision making. Rather, CAS is the sole system used to determine the dispatch status for the aircraft.

This separation of the CAS and Maintenance system message interfaces allows the evolution of the maintenance system without impacting the certification status of the aircraft. Previous maintenance systems were often encumbered by the inability to correct known maintenance issues due to the large cost of recertification. The CMC expanded upon previous maintenance systems that used low criticality maintenance functions. Once a maintenance defect is identified, there is a desire to get this issue resolved quickly rather than waiting for a new aircraft certification.

Member System Status

The CMC supports a Member System Status screen that provides a quick method to identify the status of Member Systems, based upon ATA chapter classification[4]. This function provides a color-coded display used by the line mechanic to quickly assess which systems on the aircraft are operational. ATA chapters that contain one or more faulted Member System are highlighted cyan; those with all nominal systems are displayed in white. The line mechanic can then select any ATA chapter and Member System within that chapter to displayed further details regarding its operational status. This snapshot view of all aircraft subsystems provides the line mechanic with a quick and easy method of assessing the overall health of all subsystems.

CAS Message to Maintenance Message Correlation

Expanding upon an earlier maintenance system design, the CMC features a CAS Message to Maintenance Message Correlation feature. This feature assists the line mechanic in correlating pilot-noted CAS Messages to Maintenance Messages. The pilot uses the CAS Messages to determine what actions they need to take for continued safe flight. CAS messages drive pilot action, but may not lead the mechanic to the cause of the message. The mechanic uses Maintenance Messages to direct their

[4] The Air Transport Association (ATA) has established standard identifiers for all aircraft subsystems, based on a "chapter" numbering system. This system is used in maintenance manuals and other aircraft documentation.

troubleshooting and repair activity. The CAS Message to Maintenance Message Correlation function provides a link between the two disparate users of the data and provides the mechanic what he needs to know to troubleshoot, repair and return the aircraft to service. The CAS Message to Maintenance Message correlation is defined within the Screen Builder tool, and is imported as a part of the CMC's database.

Common Look-and-Feel Interface

An objective for the CMC was to enforce a common look-and-feel, graphical interface for all maintenance items on a given aircraft type. This approach supports a reduction in the amount of training required, since all aircraft in a given "family" use the same interface. This required that all Member Systems use a common set of design objectives and screen guidelines, developed with the support of the aircraft Original Equipment Manufacturer (OEM) and enforced by the Health Management Integrator[5] with the help of the Screen Builder tool. From the perspective of the line mechanic, regardless of the aircraft subsystem being working on (e.g., Landing Gear, Environmental Control System or Avionics) all approach maintenance in the same manner.

In addition, the CMC user interface was designed to use point-and-click, which supports a variety of cockpit-mounted cursor control devices (e.g., joystick, trackball, touchpad). This alleviated the need for a keyboard interface, having proven troublesome in previous systems. Using point-and-click, line mechanic inputs are well controlled and guaranteed to be understood by the system. Further, the amount of training is reduced since the user is not required to memorize commands, syntax, etc.

Screen Builder

On each program, every Member System supplier is provided with a copy of Screen Builder, a Windows-based tool. The version of Screen Builder incorporates OEM-defined design rules and objectives. The Member System supplier uses this tool to populate their portion of the Primus Epic maintenance system. The data is submitted to the Health Management Integrator, which consolidates all of the individual submittals into a common aircraft database. This approach of collecting design data directly from each supplier facilitates the capture of maintenance related design information directly from each supplier.

Data-Driven

The CMC is a data-driven system that is configured using a database, generated by the Screen Builder Tool. The database defines the menu system of the user interface as well as the relationship between the data on the avionics bus and the data displayed to the user. The CMC interfaces directly to the avionics bus and can "see" any parameter on the bus. This ability to see parameters directly on the avionics bus allows the Member System suppliers to create maintenance screens that use data from other suppliers. The data-driven nature of the system allows suppliers and OEMs to create maintenance screens that directly read avionics parameters without having to write specific software to read and format the data.

Field Loadable

Previous aircraft maintenance system experience identified that a major issue related to maintenance code was that once maintenance related issues were identified, the issues could not be fixed until a new aircraft certification was available. The Primus Epic CMC was specifically designed to be field-loadable. There are effectively two field-loadable software entities on the module: the CMC functional code and the separately loadable database. The functional code is a part of the aircraft certified code and can only be changed as a part of the aircraft certification. The separately loaded database is a separate file that can be loaded without having to recertify the aircraft. This separation between code and database provides significant flexibility in that the database can be updated independent of aircraft certifications, as errors, deficiencies or improvements are identified.

[5] In the case of Primus Epic, Honeywell served in the role of Health Management Integrator for all OEMs. As discussed previously in the paper, this role is crucial to the success of an IVHM system.

Data Link

The CMC interfaces with the Communication Management Function and can send reports via data link to ground stations. There are several reports that are defined by the OEM and operator, depending upon the desired operation. The data link of the Current Leg report is intended to allow a ground-based operations center to make decisions on what the maintenance needs of an aircraft are prior to the aircraft landing. This approach leads to having the correct crews and parts available at the landing destination in order to rapidly return the aircraft to service, preventing delays or cancellations. Engine trend data is also automatically routed to the airline and engine supplier. As the maintenance function is driven by the database, these are features that a given operator may choose to utilize.

Aircraft Condition Monitoring Function

On Primus Epic aircraft an optional Aircraft Condition Monitoring Function (ACMF), fully integrated with the CMC. ACMF is a data-driven software application that allows the OEM or Health Management Integrator to create software programs, referred to as applications, which record specific datasets based upon trigger events. ACMF uses a PC-based tool that interfaces to the avionics data bus definition. ACMF can use any parameter on the bus for either the trigger or as a recorded parameter. ACMF applications are used to collect engine trend data on several programs and are also used to collect data used to troubleshoot design issues or help resolve difficult hardware fault isolation issues.

Significant Differences from Previous Systems

Data Storage Methodology

Most previous maintenance systems depended upon the individual Member Systems to store the fault data in their LRU/LRM. In order to display a system's stored data, a bi-directional command-request protocol was required to retrieve the data. The Primus Epic CMC instead requires Member Systems to periodically report the status of its faults, using a simple bit-oriented broadcast message. The fault status is stored locally on the CMC, for use whenever it is required by CMC processing. This change significantly simplified the fault reporting interface for Member Systems, as well as expedited CMC fault processing.

The Primus Epic CMC also changed the storage algorithm for Maintenance Messages. Previous systems stored the initial occurrence of an individual Maintenance Message and incremented a counter to identify how many additional times this Maintenance Message was reported in a given flight. Instead, the Primus Epic CMC stores every CAS and Maintenance Message transition and tags each with Time, Date and Flight Leg. This permits the CMC to identify intermittent patterns suggesting failure trends and/or design deficiencies.

CMC Remote Terminal Connectivity

Commercial airlines are schedule-driven. On-time departures are the goal, seeking to avoid inconveniencing the flying public. To support this goal, today's aircraft must support quick turn times and rapid troubleshooting. While typical maintenance system installations provide a user interface in the cockpit, by nature it is not an environment that readily facilitates maintenance activities. To address this issue, the Primus Epic supports remote connectivity to the CMC via the aircraft local-area network (LAN). Connections points are provided at key locations around the aircraft to support troubleshooting outside of the cockpit. Using laptop PCs, an interface is presented to the line mechanic that is identical to that displayed on the cockpit display. This permits the mechanic to see the maintenance screens and CAS messages outside the cockpit. By providing CMC access in the immediate vicinity of the work being performed, the mechanic does not have to travel back and forth to the cockpit, facilitating parallel activities by mechanics and flight crews, enabling both to be more efficient.

On-Line Linked Manuals

Using the CMC Remote Terminal and a commercial browser, the line mechanic can view aircraft maintenance and procedure manuals. The CMC software provides an interface that passes a hotlink to the browser, which is used to define the relevant section of the manuals for a given Maintenance Message. This permits the system to quickly access and display the relevant section of the aircraft manual, eliminating the manual steps required to find the manual and look up the process, ultimately aiding in the rapid fault isolation and repair of the aircraft.

Challenges/Lessons Learned

The major technical issue experienced with the Primus Epic CMC was caused by the amount of I/O processing due to the number of Member Systems and Maintenance Messages. As aircraft certification approached, some CMC databases (depending upon the aircraft type) had grown to nearly double the size of original estimates. This required that the hardware resources be increased in order to fulfill intended functionality.

Although every program is faced with technical challenges, the greatest challenges for Primus Epic were "programmatic" in nature. With the significant increase in the level of system integration[6] that Primus Epic supported it was extremely difficult to keep Member System suppliers and OEMs focused on maintenance issues. The Primus Epic programs that most effectively utilized CMC capabilities were those in which the OEM created and maintained a qualified staff of employees dedicated to aircraft maintenance. Programs that were unable to achieve focus were forced to scramble to have effective maintenance capability at entry into service. The escalating expectations and objectives of the maintenance system required skilled engineering personnel. One major error made in several of the Primus Epic programs was not having the maintenance function represented by a maintainability specialist at design reviews and integration testing. Several suppliers and OEMs did not remain focused on maintenance-related issues as the system and software designs evolved.

The CMC objectives included having significant capability that could be used to support manufacturing needs. The CMC's data-driven approach allows the use of a special "debug" database while the aircraft travels down the production line (supporting the aircraft build process), to be replaced later with the official in-service database when the aircraft was delivered. Unfortunately this capability was never used due to the lack of focus by OEMs and Member System suppliers.

Significant fault modeling capability exists within the CMC. This capability can be used to reduce the storage of nuisance messages and to support fault isolation. The modeling features require that equations and models be built that span multiple systems. Initial plans called for using the flight test to collect data to support this modeling. The lack of software maturity during flight tests meant that there was little maintenance data collected during the flight test program. This represented a huge impact to maintenance maturity at entry-into service.

Benefits Achieved

The Primus Epic maintenance system is supported by more than 200 aircraft Member Systems. The centralized maintenance interface supported by the CMC allows literally nose-to-tail coverage on most aircraft. The ability for Member System suppliers to create maintenance-related screens using the provided tools meant that the suppliers were able to create screens to support maintenance without having to design, write and test maintenance code. As an example, if a Member System supplier needed data from four or five other systems on the aircraft, they could implement a screen using the tools that would allow them to monitor the parameters from each of these producing systems. The separately loaded database that defines the Maintenance Screens and Maintenance Messages allows rapid updates and allows the maintenance system to evolve as issues are discovered.

Boeing 787 CIS/MS

High-Level Overview

The Boeing 787 Crew Information System (CIS) provides a networking infrastructure (refer to Figure 6), which enables airborne functions to interact seamlessly with ground components and a computing environment capable of hosting

[6] Unlike previous modular avionics systems, Primus Epic aircraft not only integrated basic avionics, but also included utility system control (e.g., hydraulics, power distribution, lighting control,) and third-party subsystems (e.g., vibration monitoring, fire detection/suppression, etc.).

RTCA/DO-178B[7] level-D and Level-E software applications

Hosted by the CIS are various standard applications, including the Maintenance System (MS), Electronic Flight Bag, Data Loader, Onboard Boeing Electronic Distribution of Software, Crew Information System Services, Flight Deck Printer, and Terminal Wireless LAN Unit (TWLU).

In addition, airlines may select options such as Crew Wireless LAN Unit (CWLU), Connexion by Boeing, Electronic Maintenance Manuals, and Airplane Health Management. A second CIS/MS File Server Module may be added to increase system availability and provide fault tolerant mass storage. Or an operator may choose to add computing resources and custom software applications.

Key Features

The 787 OMS is based on the highly regarded Boeing 777 CMC and ACMF. These software applications utilize the CIS/MS resources to provide a stand-alone onboard maintenance capability to economically extend the diagnostics and prognostics to ground-based systems.

The CMC uses model-based diagnostics to drive Fault Processing, Ground Tests, and to display textual information to the mechanic. The Fault Model encodes the observable symptoms for each fault condition based on the modeled effects of each fault condition within the member system and the connectivity of LRUs within the aircraft.

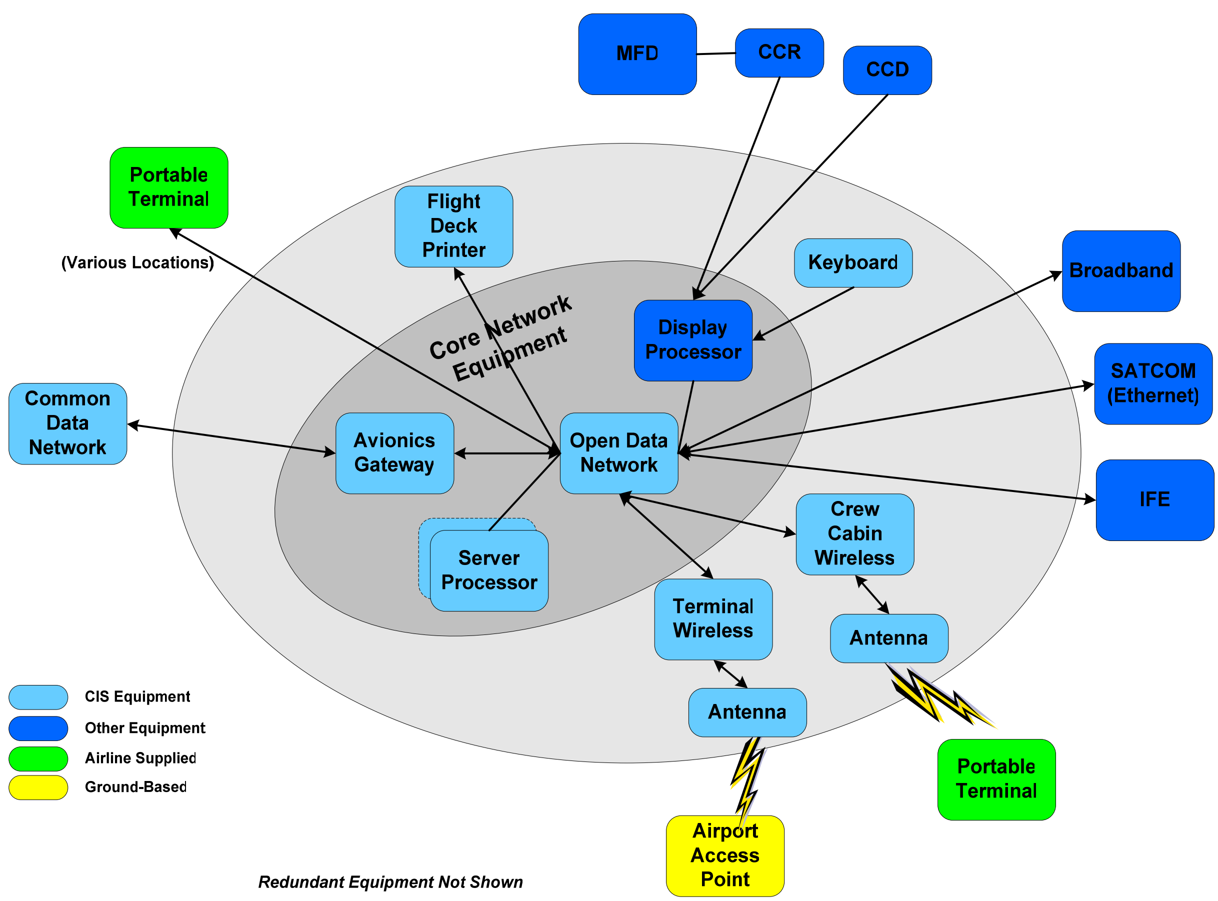

Figure 6 Crew Information System

[7] This standard describes the software design-assurance processed adopted by the FAA for use in commercial aviation (visit **www.rtca.org** for more information).

Each system on the aircraft is responsible for fault detection and reporting. The reporting system, also referred to as a Member System, communicates with the CMC using an aircraft-wide standard protocol. This protocol provides for fault reporting, configuration reporting, and commanded ground tests.

Model information is contained in a separately loadable database referred to as the Loadable Diagnostic Information (LDI).

The LDI is created by a Diagnostic Modeling Development Tool (DMDT). The purpose of the DMDT is to collect and validate the Fault Model for the aircraft. The tool is seeded by imports from various sources such as the aircraft Interface Control Document (ICD), CAS design document and the Failure Modes and Effects Analysis. Aircraft system designers enter system specific information and links to complete the basic model.

The aircraft system integrator completes the model by connecting the faulted system outputs to the affected system inputs. This aircraft level modeling determines fault consolidation, fault cascade effect removal and ensures correct Flight Deck Effect (FDE) correlation.

ACMF provides a programmable method for triggering custom data reports. Report triggers can be defined using ICD signals combined with logic units to collect sample data at a predefined rate and time prior to and after the trigger event.

Resulting reports can be stored locally on the CIS hard drive, as well as down-linked via Airborne Communications Addressing and Reporting System (ACARS) or one of the available broad band communication paths (e.g., Gatelink, Connexion or Swift64 Satellite).

Reports are defined using the Ground Based Software Tool (GBST), which provides the basic framework to support Airline Modifiable Information (AMI) development and has built-in functionality for supporting programmable functionality in the CMC.

The above systems provide interfaces to aircraft communication systems, airline applications and information systems, in an open and cost-effective architecture that is easily extended and adapted for current and future operator needs.

Significant Differences from Previous Systems

Maintenance System control and display is available through several user interfaces. Web-based technology is used for the primary interface and ARINC-661 is provided as a backup.

The primary interface to the maintenance system is a COTS PC using a typical web-browser interface. Unlike the Boeing 777, these devices are not certified or installed in the aircraft. An operator may choose to stow a laptop style computer on the aircraft for convenience.

In the event that the primary means of Maintenance System control and display (i.e., a laptop computer) is not available, one of the cockpit displays is equipped to provide the minimum functionality necessary to prepare the aircraft for dispatch.

Basic to the 787 aircraft is the TWLU. This provides the aircraft side of the Gatelink connectivity. Gatelink provides a cost effective means of moving data on and off the aircraft. Commercial wireless standards (e.g., IEEE 802.11) are used to enable the operator to electronically access the aircraft when it is located at the gate.

The optional CWLU provides the ability to use a wireless laptop computer in the proximity of the aircraft to perform all of the available Maintenance System control and display functionality. The CWLU system provides necessary security and allows for multiple simultaneous users.

Previous maintenance systems provided references to procedures such as Fault Isolation, Remove and Replace, etc. This Maintenance System will provide links to the electronic aircraft maintenance manuals, allowing instant access to the detailed procedures without leaving the aircraft. This will reinforce following proper maintenance actions.

Boeing will deploy their implementation of Electronic Distribution of Software (ARINC-666). Loadable software will be uploaded using

Boeing Electronic Distribution of Software via one of the available broadband links.

After the software has been up-linked and stored on the aircraft they are available to mechanics for installation into appropriate LRUs.

Previously parametric data collection was defined either by an AMI or the airline. Parametric data can now be remotely defined and requests up-linked real time. Parametric data collection can be triggered by a fault report and stored or down-linked for analysis.

Legacy Quick Access Recorder (QAR) functionality is included as part of ACMF. The desired parameters are defined by the operator using the GBST to create an AMI. During the flight, selected parameters are logged to the hard drive in the CIS/MS File Server Module. The data files can be down loaded or down-linked as required.

Anticipated Challenges

In order to take advantages of aircraft wireless connectivity it is necessary to address all aspects of network security. This becomes increasingly important as the sphere of accessibility expands to include the public Internet. This is an area of safety concern for certification authorities and of business concern for the aircraft operators.

A security analysis is necessary to ensure that unauthorized access is highly unlikely. The analysis should take into account all potential safety concerns and address business issues.

Unlike a conventional Safety Analysis, security threats are not bounded and change over time. So the probabilities that are conveniently applied to software development are not applicable.

A layered security policy approach will be implemented that makes increasingly difficult access to safety critical systems. The security policy is defined in terms of the "zones" (shown in Figure 7) described below:

- The Closed Network consists of the Common Data Network and all hardware and applications connected or resident on that network, with the exception of the CIS itself.
- The Airplane Private Network consists of the Open Data Network, the CIS system, the In-Flight Entertainment system, and the portable terminals.
- The Private Network consists of the Airplane Private Network, SATCOM, Connexion by Boeing, and the airline operations networks.
- The Airplane Public Network consists of Passengers and Passenger Devices.
- The Public Network consists of the Airplane Public Network, and Public Internet Users.

Even though the TWLU will be basic on the 787 aircraft, the definition and standardization of the required ground infrastructure is lagging.

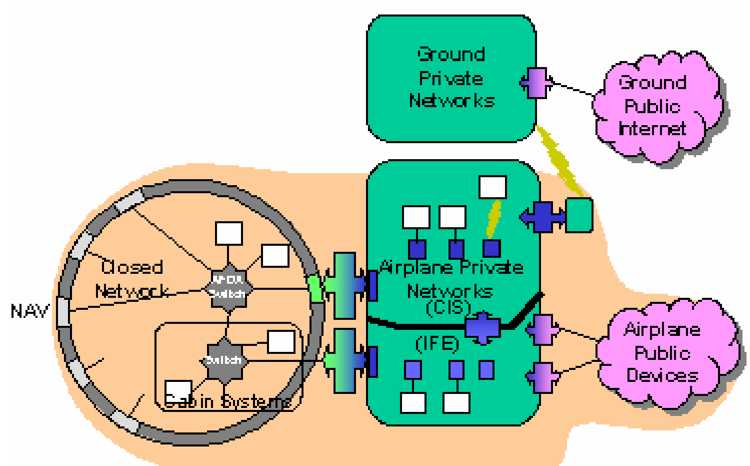

Figure 7 Security Zones

To achieve maximum Gatelink benefit the aircraft should join the operator's network automatically when at the gate at any airport in the world. Changing technologies, protocol standards, encryption technology export restrictions and country licensing agreements make it difficult to implement an aircraft system that achieves universal airport access.

Additionally, airlines may be prohibited from fielding their own installations and will be subjugated to the wireless network installed and operated by individual airport authorities.

Anticipated Benefits

The Boeing 777 Maintenance System provides a solid foundation for the 787, from which to incremental improvements and new features will be added. This low risk approach makes possible a mature system available early in the development to facilitate the aircraft build and factory checkout. Anticipated benefits of the new system include:

- High Maintenance Systems availability is balanced with low cost computing resources to optimize performance and cost. Maintenance functionality is preserved after any single fault by displaying maintenance information on forward flight deck displays.
- Model based diagnostics utilizing a separately loadable database facilitates production changes and model corrections with minimum certification impact.
- No costly certification of the maintenance user interface. The aircraft operator is able to purchase low cost computers for use by the mechanics to access the Maintenance System.
- Eliminate of QAR hardware on the 787 by integrating the functionality in ACMF software.
- Wireless remote access allows a mechanic to access the Maintenance System at the gate when the plane arrives. Access to ground tests and CAS maintenance pages are also available to the mechanic
- Wireless remote access also reduces maintenance time by allowing a mechanic to electronically de-energize and collar a "soft" circuit breaker. Previously a remove and replace procedure would require multiple trips to the flight deck to physically pull or push a circuit breaker.
- Boeing Electronic Distribution of Software will eliminate any need for physical media (e.g., floppy disk, CDs, memory cards). Loadable software, documents, etc. will move electronically from the supplier to the aircraft. This will reduce the cost of producing, distributing and storing media. It also insulates from media obsolescence over the operating life of the aircraft.

Intelligent Vehicles/Sense & Respond

High-Level Overview

To this point, discussion has focused on the benefits derived from advancements in the integrated health and information systems deployed onboard commercial aircraft. While significant progress has been made, a step-change of improvement is now feasible. Technology advances in information transfer and wireless communication enables the removal of prior system design constraints. To realize these significant gains, the entire end-to-end process used to sense anomalies and respond with appropriate action must be reexamined, focusing on the operational innovations that can be enabled through the powerful combination of IVHM, information technology, and the Internet.

The Next Wave of Improvement

Current generation IVHM solutions are constrained by the fact that high fidelity access to many of the functions requires one to be in close proximity of the vehicle. Yet the majority of the expertise and resource best poised to analyze, decide and act on the outputs are widely distributed in time and space from the aircraft. Today's IVHM systems are designed to serve line mechanics as the primary user while they are at or near the vehicle. Information-rich user interfaces are available mainly through manual displays. Bulk data download requires human intervention with laptop computers and flash memory cards to gain access to detailed performance and event data. Although remote messaging and alerting are available via aircraft datalinks today (e.g., ACARS), this method is roughly equivalent to the early days of accessing mainframes using 1200 baud dial-up modems and terminal servers.

The rapid advances in wireless communications and information technology, when tightly integrated with IVHM systems, can now provide the tools needed to rethink the process of detection, to action, to correction. Consider today's Formula 1 racing operation in which each race car is outfitted with hundreds of sensors, wirelessly streaming data back to an operational and analytical hub located in the team van parked in the infield. This data is analyzed by computers and vehicle experts who in turn forward instructions directly to the pit crew, the race strategists and the driver allowing real time adjustments to improve performance and capability. Bulk data is also collected and forwarded immediately to automotive engineers back at the home office for analysis, where the planning begins for vehicle design modifications and upgrades before the next race.

The innovation highlighted by this example is not a technological innovation, rather it is actually an operational and process innovation. It is through operational innovations such as this that commercial aviation will realize the next wave of improvements, enabled by IVHM and information technology. Sensing and responding to anomalies in real time, coupled with the ability to engage a global community of resources and expertise to resolve issues, will enable industry to move from reactive, to proactive, to predictive strategies. This will be characterized by a shift to a network centric approach to operations. Figure 8 is an example of a network centric "sense and respond" process.

Enabling the Shift to Sense & Respond Network Centric Operations

Enabling a shift to network centric operations first requires a deeper understanding of the value proposition for vehicle operations, as well as developing a much broader view of the end-to-end system supporting that value proposition. The "Sense & Respond" framework illustrated by Figure 9 is a useful tool to structure solutions. The framework helps one to first understand the

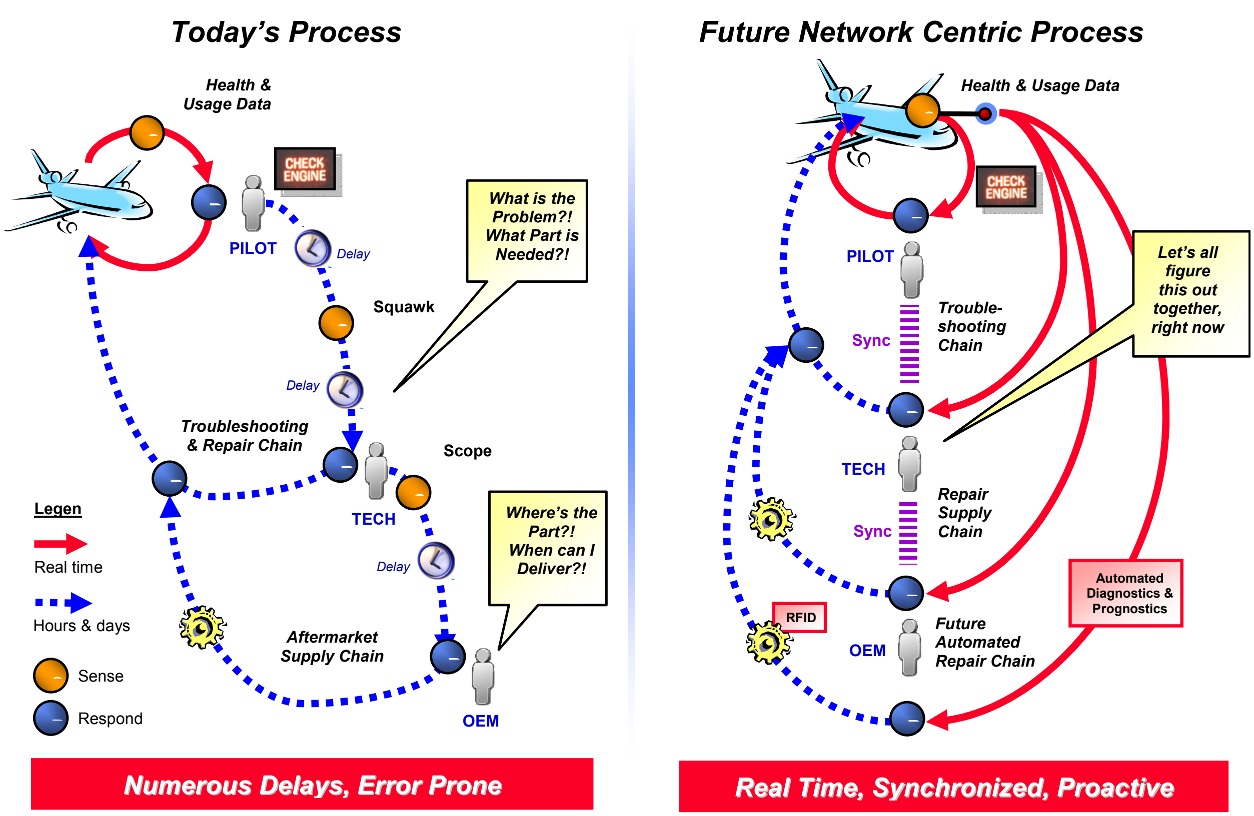

Figure 8 Network Centric "Sense & Respond" Process

value proposition to the customer, the corresponding end-to-end process that provides that value, and finally the requirements for enabling technologies, systems, and resources forming the process infrastructure.

The perspective actually starts, not with the enabling technologies, but at the operator. It is here where a deeper understanding of the operational goals and measurements must be gained. What is to be achieved and how is it measured? What do operators value and how much? Is it safety, dispatch availability, cost of ownership or something else? Are all equally weighted, or are they ranked in importance? Once these areas of value are understood, current performance can be baselined by measuring event rates, cycle times, costs, etc. A deep understanding of value from the customer's perspective is a vital first step in order to accurately determine the requirements for new processes and the enabling technologies and resources.

With a deeper understanding of the value equation, the capability to create an end-to-end process innovation can be evaluated by examining four elements of the new process.

1. Connect - Can the right data (IVHM outputs), knowledge and resources be connected together?
2. Simplify - Can the end-to-end process be simplified through easy and timely access to information that enables faster decisions and faster responses?
3. Clarify - Can the situation by clarified through context and accurate information, allowing one to act with precision and foresight?
4. Deliver - Can the necessary response (plans, parts, procedures, people, etc.) be delivered that affects the value equation in question?

Once reasonable insights into these questions are established, requirements on the enabling infrastructure, applications, and value delivery systems can then be explored. In this framework, infrastructure includes elements such as onboard sensors, data acquisition units, telemetry, data storage, security, user interfaces, middleware functions, and integration with other systems. Applications include specific software functions necessary to analyze and present information,

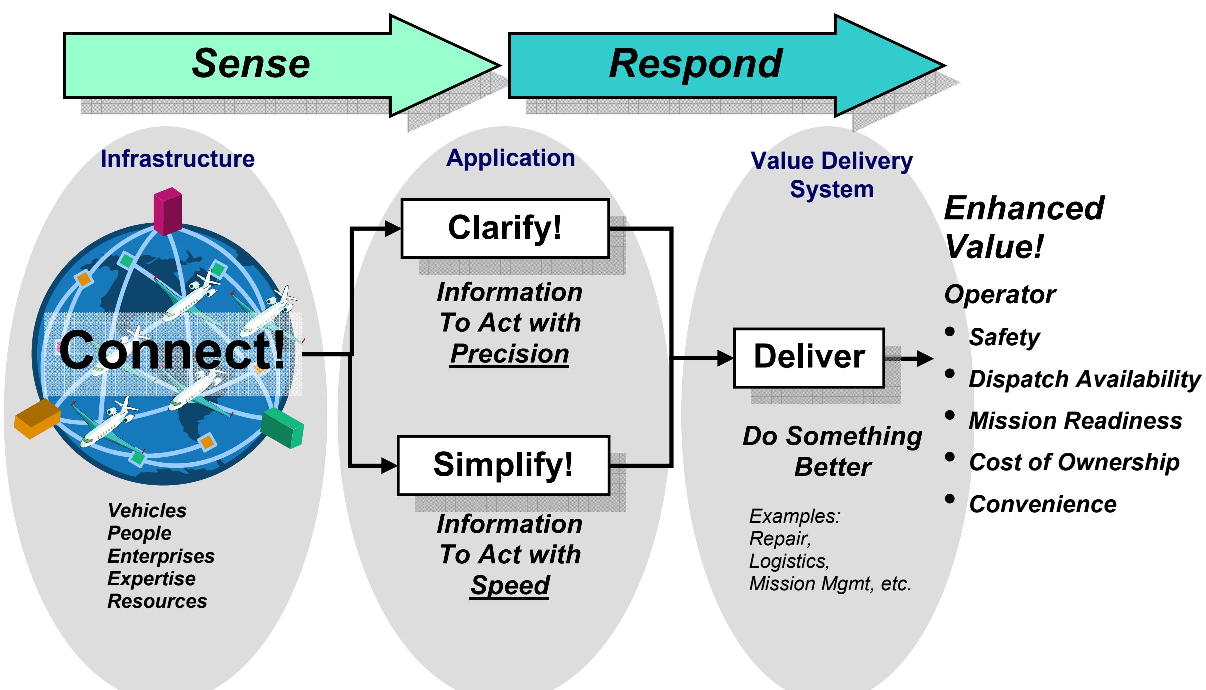

Figure 9 Sense & Respond Framework

create context, and supporting decisions and actions. Finally, the value delivery systems include elements of service such as repairs, parts distribution, logistics, mission management and others.

Barriers to Adoption

It's relatively easy to foresee significant improvements through the use of IVHM and Sense & Respond approaches. Yet realizing these benefits is not without challenge. There are numerous barriers that prevent moving this concept forward, most of which are not technological. The biggest barrier is most likely the resistance to change presented by industry. Aerospace, being a long cycle industry, typically advances and innovates when new aircraft platforms are introduced. The cost to re-certify new configurations or procedures creates a large hurdle for introducing innovations in existing aircraft. Further, the large capital investments in tools and supporting resources made when introducing a new platform require that they be utilized extensively over a long period of time to provide an appropriate return on investment. This existing base of capital assets creates another barrier to change by forcing new investments to be deferred until an ROI can be achieved, or by requiring the new techniques to adapt to the constraints of the legacy systems and processes.

Next Steps

Although these barriers are challenging, Honeywell is committed to advancing the industry by working closely with customers to insert innovations while addressing these barriers. Investments are currently being made in all three areas of the Sense & Respond enabling framework.

- <u>Infrastructure</u> - Scalable architectures are being designed that take advantage of COTS and the Internet to lower the capital cost of the information infrastructure while emphasizing data security, accuracy, and privacy.
- <u>Applications</u> - Web-based software platforms are being developed that integrate existing tools and capabilities such as condition monitoring, diagnostic modeling, predictive trend monitoring and distributed case-based reasoning.
- <u>Value Delivery Systems</u> - Sense & Respond service processes are being deployed that take advantage of IVHM functions embedded in active commercial propulsion systems and integrated avionics platforms. The initial focus is on demonstrating improvements in dispatch availability by helping customers reduce the detection to action cycle and pro-actively manage unscheduled maintenance events.

Honeywell will be piloting Sense & Respond solutions on the TFE-731 and HTF-7000 turbine engines later in 2005 and throughout 2006. The pilot program will include onboard IVHM functions, wireless data downloads, ground-based data services and diagnostics, made accessible via a web platform that enables the new service processes.

Future Trends

In the field of commercial aviation, new technologies continue to be investigated. Unlike the past, however, they are driven by the need to bring value to the customer, rather than pure technology. In the examples discussed in this paper, many of the innovations find their roots in present day technologies (e.g., wireless and Internet accessibility), being combined in new ways to provide value and service to customers. Honeywell is convinced that advances such as these will help commercial aviation achieve significant improvements in flight safety, dispatch availability and cost of ownership.

As noted earlier in Figure 4, maintenance systems for commercial aviation have undergone a significant evolution since the introduction of simple BIT tests in the early 1980s. This evolution continues with technology advances in IVHM and process innovations such as Sense & Respond. While many of these technologies are just as applicable to the exploration of space as they are to commercial aviation travel, it must be understood that the majority of IVHM technologies used in commercial aviation were developed in support of maintenance. In contrast, the needs of next generation spacecraft (e.g., Crew Exploration Vehicle) will depend upon the use of IVHM technologies in support of vehicle automation, vehicle reconfigurablity, mission planning and execution (in addition to maintenance). By definition, these uses are of higher-criticality than vehicle maintenance and must be developed and tested to higher levels of scrutiny. It is in this area where more research and development will be needed to adapt commercial IVHM technologies to the applications of human spaceflight.

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